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PIEZO-ELECTRIC CRYSTALS AS VIBRATION CONTROL DEVICES FOR FLEXIBLE SPACECRAFT STRUCTURES

FINAL REPORT

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PIEZO-ELECTRIC CRYSTALS AS VIBRATION CONTROL DEVICES FOR FLEXIBLE SPACECRAFT STRUCTURES

Summary

The objective of this research was to explore the use of piezo-electric crystals to control vibratory motion of flexible spacecraft structures such as a space station, deployable solar arrays and antennas. This experimental and analytical investigation had a focus on the proof-of-concept demonstration of piezo-electric crystals as vibration actuators on scale models of real world space structures. This work was conducted under the sponsorship of NASA JSC- Regional University Grant Program and in consultation with the project engineers of Loads and Structural Dynamics Laboratory at Johnson Space Center. The total cost of the project was $58,969.

Piezo-electric crystals worked well as actuators in controlling vibrations of a steel cantilever beam in the frequency range of 25 to 2000 Hz. Although their actuation was small at low frequencies, they performed very well at higher frequencies. The crystal actuators adaptation became a problem in case of large flexible space structure such as a deployable solar boom. Its size required the use of stacked crystals to generate high control force. The low frequency and excitation force of the procured crystals were limited and the vibration control experiments on large, flexible ASTROMAST using piezo-crystals were not successful. These experiments however, suggested ways of designing and embedding large size crystal actuators to control selected modes of space structures. A research paper describing these experiences was presented at the NASA's Duel-Use Technology Conference in February of 1994.

1. Introduction

Piezo-electric crystals have been used before as sensors [1] to identify resonances of structural components. Recent developments in piezo-ceramic technology suggested their use as actuators [2] and the present research emphasized their use as actuators to control vibrations of a structure such as a deployable solar boom. Astro Aerospace Corporation manufactured lattice mast, Astromast was the test specimen for implementing crystal control experiments. Details of Astromast were described in reference [3].

2. Vibration Control: Analysis and Experiments

The Principal Investigator after confirming with Mr. David A. Hamilton designed an experiment to monitor and control resonant vibrations of a cantilever beam by piezo-electric crystals. The following paragraphs describe the experiments on a uniform cantilever and deployable solar boom.

2a. Cantilever Beam Experiment

Figure 1 shows the layout of the experiment. The experiment consisted of exciting a cantilever beam in its flexural mode by an exciter crystal and inducing a negative effect by a controller crystal. The control crystal at the bottom of the beam after receiving an inverted, 180° phase shifted voltage signal applied excitation force causing the beam to move in the opposite direction. The 180° phase shift of the control signal was achieved with reference to the accelerometer response signal. The accelerometer was mounted at the tip of the beam. Figure 2 shows the schematic of the closed loop control instrumentation.

Two experiments were conducted -- the first with the controller crystal at two-thirds length and the second with the controller crystal near the root of the beam. Table I summarizes the results. The following were observed: The crystals were effective in controlling the vibrations; crystals worked well at higher frequencies compared to lower frequencies; appreciable phase between the excitation and response was evident; and the beam response became unstable at higher control voltages. Larger control voltages and custom design crystals were required for real-world structures.

The fundamental mode of the beam at 29 Hz was difficult to excite because of two reasons -- the motion at low frequencies was transferred to the base, and the crystal is not effective at low frequencies. The vibration reduction for the second, third and fourth flexural modes was substantial. A typical oscillograph signals at 184 Hz in Figures 3 (a) and 3 (b) with and without control crystal indicated the reduction in vibration. Similar signatures were recorded for other resonances at 29, 522, 1021, and 1680 Hz. More beneficial effects were observed when the exciter crystal was located near the fixed end of the beam. With the inverter, it was possible to introduce nearly 180° phase shift to achieve vibration reduction. However, a precise matching of phase between the excitation and response would completely reduce the resonant vibrations of the test beam.

2b. Astromast Vibrations

The finite-element modeling of the 15 bay, 21-ft long, 29.5-inch diameter boom consisted of 81 nodes and 378 rod elements. The basic model had treated all battens as straight rods with circular cross-section. Friction at the joints was neglected, and the aluminum rotating joints were considered as concentrated masses. The mechanical properties as supplied by Astro Aerospace Corporation for S-glass material were used. The analytical model imposed partial rotational constraints for the longerons joints at the end plates. ABAQUS finite-element software was used to determine the first 15 natural frequencies and mode shapes. At the first glance, it was difficult to discern the mode shapes from the results. The mode participation factors with dominant component of motion helped identify mode shapes of this boom. Three distinct motions seemed possible -- torsion about the length (x) axis, and bending motion about two perpendicular (y-z) axes. Insignificant modal participation factors at other frequencies indicated un-coupled motion between x and z axis and also x and y axis.

In preparation for vibration tests, the mast has been deployed and supported at both ends, electrodynamic-piezo-electric shaker with matching network provided a sine excitation at mid-length of the boom. A rowing accelerometer was used and responses were analyzed in time and frequency domains to identify resonances. Lissajous figures were generated to confirm the resonances. Figure 4 shows the set up for the ASTROMAST vibration test. Measured and predicted frequencies of the mast are compared in Table II. A good agreement was seen between predicted and measured frequencies. It was difficult, however, to match the predicted mode shapes with the measured because of limited instrumentation. Although the test indicated closely spaced resonances around 62 and 86 Hz, the analysis did not delineate these modes.

This data provided a basis to try crystal controllers at selected resonance frequencies.

The results from these experiments were presented to a NASA sponsored conference [4].

3. Conclusions

Piezo-electric crystals worked well in controlling vibrations of a cantilever beam. The crystal control experiments on the solar boom were not successful in the present research. The deployable ASTROMAST solar boom was finite-element modelled and sine dwell tested. A good agreement between the predicted and measured frequencies was observed. A side benefit to this JSC-University research is that many students were enthusiastic about vibrations of deployable space structures. Piezo-electric crystals although showed distinct promise for their application for small components, high voltages and custom designs are needed to control large flexible space structures. Future research will attempt to adapt large size crystals to achieve vibration reduction in large structures.

4. Acknowledgements

The Principal Investigator thanks Johnson Space Center for the financial support to undertake this research. Special thanks are due to Mr. David A. Hamilton, Manager of Loads and Structural Dynamics Laboratory at JSC for advice, and Astro Aerospace for supplying the test object.

5. References

1. Midturi, Swaminadham et al., "Identification of Resonant Frequencies of Rotating Beams with the Use of PZT Crystals," SESA Experimental Mechanics, pp. 76-80, February 1979.
2. "Some Design Considerations in the Use of Bimorphs & Motor Transducers," Morgan Matroc, Inc. Report, TP-237, 1993.
3. "ASTROMAST for Space Applications," Astro Aerospace Corporation Report, AAC-B-004, July 1985.
4. Midturi, Swaminadham and David A. Hamilton, "Piezo-Electric Crystals as Vibration Control Devices for Flexible Spacecraft Structures," NASA's Dual-use Technology Conference, February 1994.

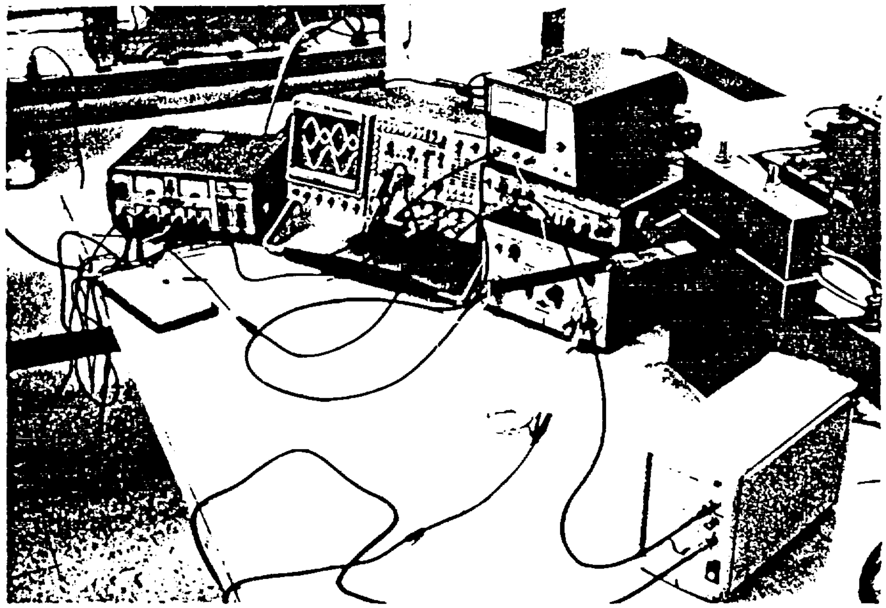

Figure 1. Cantilever Beam Crystal Control Instrumentation

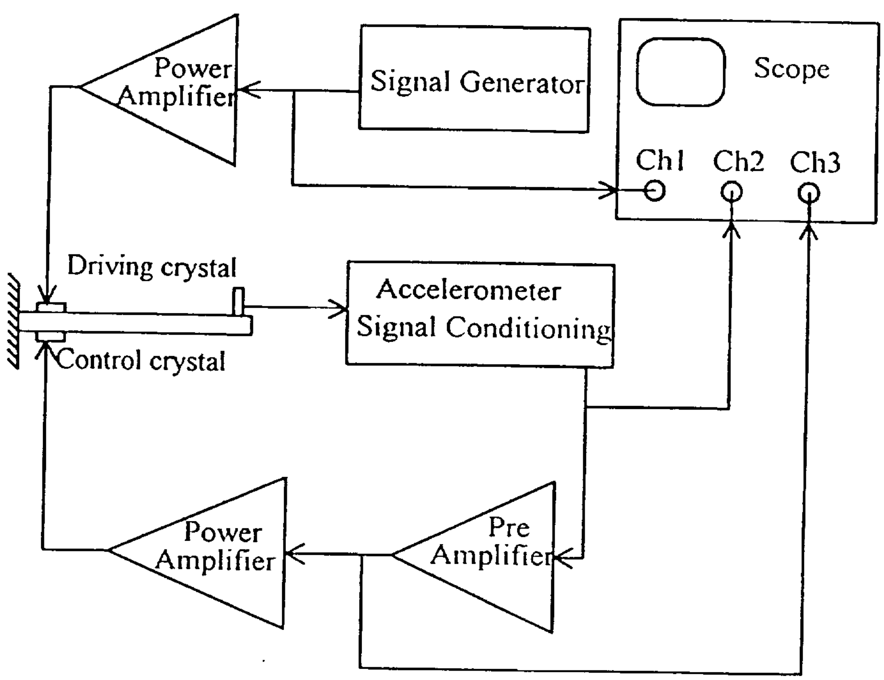

Figure 2. Schematic of Closed Loop Vibration Control Instrumentation

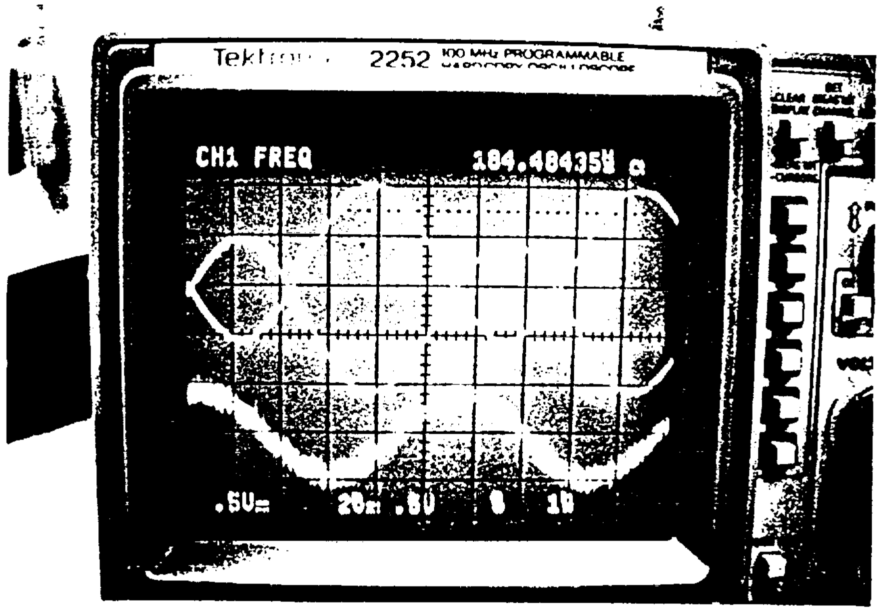

Figure 3a. Beam Response Signal (Bottom) at 184 Hz with Control Crystal OFF.

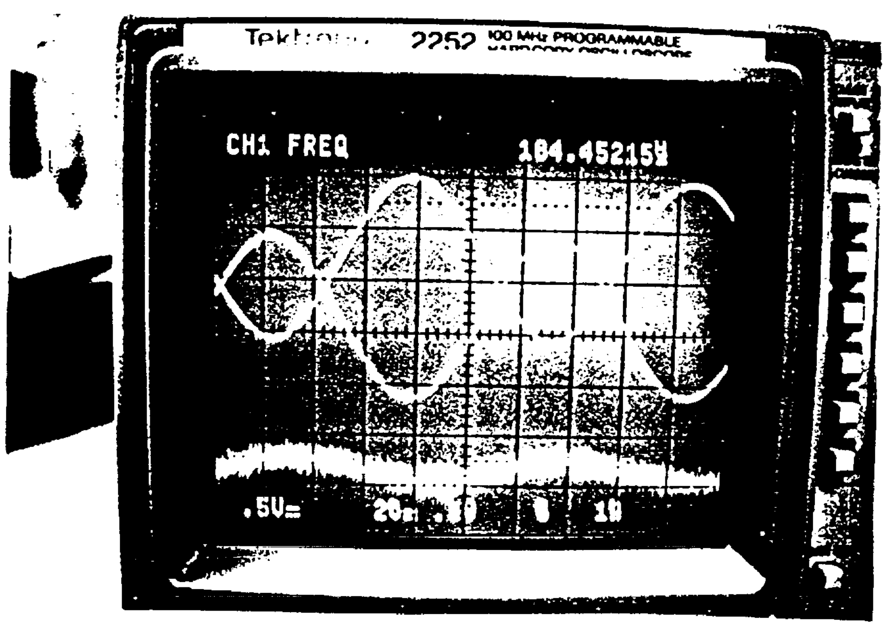

Figure 3b. Beam Response Signal (Bottom) at 184 Hz with Control Crystal ON.

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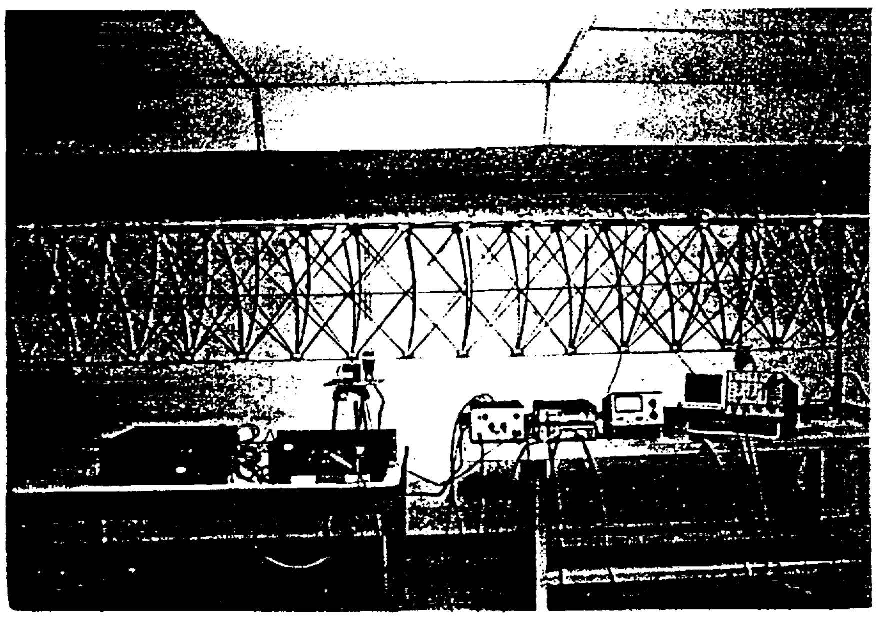


Figure 4. ASTROMAST Under Vibration Test

TABLE I PIEZO ELECTRIC CRYSTAL (PZT 5, 1 x 0.5 x 0.040 inch)
ACTUATOR EXPERIMENTS ON A STEEL CANTILEVER BEAM (12 x 1.14 x 0.139 inch)

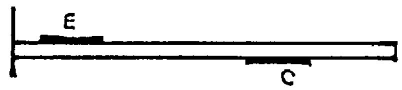
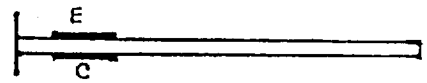
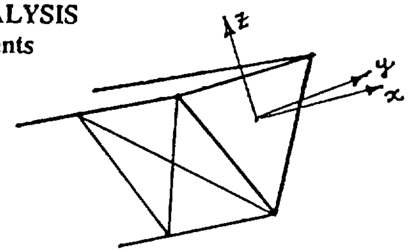
MODE	EXPERIMENT I				EXPERIMENT II			
	 				 			
	Frequency (Hz)	Exciter (E)	Control (C)	BOTH (E+C)	Frequency (Hz)	Exciter (E)	Control (C)	BOTH (E+C)
1	29.7	7.8 mv	3 mv	–	29.2	7.02 mv	6.0 mv	2 mv
2	187.6	160 mv	160 mv	50	182.8	78 mv	78 mv	35 mv
3	522.2	300 mv	302 mv	71	506.5	150 mv	150.5 mv	29 mv
4	1021	508 mv	506 mv	385	984.3	820 mv	665 mv	205 mv
5	1680	254 mv	200 mv	123	1622	1290 mv	1300 mv	205 mv

TABLE II SOLAR BOOM VIBRATION ANALYSIS
FEM MODEL: 81 Nodes, 378 Rod Elements



MATERIAL PROPERTIES: E = 8.84E + 06 psi, Poisson's Ratio = 0.25,
Mass Density = 2.6E - 04 lbm/in^3;
Radius of longeron = ⅝ inch; Batten = 0.314 in.
Diameter, D = 29.5 in

MODE	Frequency (ABAQUS)	Frequency Experimental (Hz)	Mode Participation Factors X	Y	Z	X_R	Y_R	Z_R	COMMENTS
1	23.9	20.7				18.04			Torsion about x
2	29.2	27.4						154.4	Bending about z
3	32.6	30.6					-154.8		Bending about y
4	33.1	37.4						-2.5	Combined x and z
5	58.2	45.1	Insignificant Motion						
6	61.65	62.4 64.5 65.1					 84.9	-86.5	Bending about z Bending about y
7	86.6	82.5 86.6 89.3				 5.5			Torsion about x
8	94.9	95					-68.1		Bending about y
9	97.1								